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Research Article

Quantifying the Impact of Innovation-Driven Supply Factors on Economic Growth and Innovation-Development Security

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Abstract. The accelerating transition toward knowledge-based and innovation-oriented economies has intensified the need to assess how innovation-driven supply factors influence economic growth and innovation-development security. Although many studies have examined the relationship between innovation, productivity, and competitiveness, important research gaps remain, particularly regarding the quantitative assessment of innovation-driven macroeconomic factors within the aggregate supply framework and their direct contribution to innovation security as an element of national economic resilience. Furthermore, existing international evaluation approaches, including the European Innovation Scoreboard, do not adequately capture systemic sustainability, vulnerability thresholds, or stability margins of innovation systems. Addressing these limitations, this study provides a scientifically grounded quantitative evaluation of the contribution of classical aggregate supply macro factors and innovation-related macro factors to economic growth, while operationalising resulting indicators of innovation-development security for comparative assessment across potential (Ukraine, Georgia), actual (Poland), and former (United Kingdom) EU member states. A neoclassical Cobb–Douglas production function embedded within a Keynesian analytical framework is applied, incorporating Hicks-neutral technical progress, constant returns to scale, and diminishing marginal productivity. Innovation drivers—such as gross domestic expenditure on R&D, innovation expenditure, and total education expenditure—are integrated into a dynamic model establishing causal relationships between inputs and outputs without requiring extended time-series datasets. The Solow residual methodology formalises the contribution of innovation and classical macroeconomic determinants to total factor productivity and economic growth, while key innovation security indicators are proposed, supported by defined safe-existence boundaries. The results demonstrate a substantial and heterogeneous influence of innovation inputs on growth dynamics, resilience, and systemic stability, revealing structural asymmetries and potential vulnerabilities. The study concludes that innovation is not only a fundamental driver of economic development but also a crucial determinant of innovation-development security, offering policymakers analytical tools for monitoring resilience, identifying risks, and strengthening long-term competitiveness.

Keywords: innovation-driven growth; aggregate supply; economic growth; innovation security; innovation indicators.

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1. Introduction

The concept of innovation-driven economic growth, with its clear and undeniable advantages, remains one of the most compelling paradigms in contemporary economic thought. In the twenty-first century, the innovation-driven economy has emerged as a fundamental priority for national development, providing the most effective mechanism for achieving dynamic and sustainable growth. Innovation not only enhances productivity but also promotes human development, environmental sustainability, social security, competitiveness, and national resilience. However, the realisation of innovation-driven growth requires an adequate resource base and the stimulation of scientific and technological activity. No country can sustain competitiveness without systematic support for innovation and research.

Investment and innovation activity, therefore, serve as catalysts for long-term economic progress and as sensitive indicators of broader social and economic transformations. Governments worldwide have recognised this imperative, embedding innovation at the centre of strategic development agendas and policy frameworks [1].

Despite the ubiquity of concepts such as “innovation,” “innovation processes,” and “innovation potential,” ambiguity persists regarding their precise quantitative measurement and their relationship with innovation security. The key challenge lies in defining innovation in measurable economic terms – expressed through innovation indicators that capture its presence, efficiency, and contribution to GDP growth, as well as its role in maintaining the stability and security of innovative development. In a strict mathematical sense, this requires quantifying innovation as a measurable variable: determining whether innovation is present (“yes” or “no”), calculating its proportion in annual growth among other macro factors, assessing its share in overall GDP expansion, and evaluating its effectiveness.

As Barnett [2] rightly observed, “what can be measured can be managed.” Hence, understanding how macro-level innovation factors influence both economic growth and innovation-development security is essential for formulating evidence-based policies, enhancing competitiveness, and ensuring the sustainable resilience of national economies. Such assessments are also crucial for designing evidence-based policy frameworks, national innovation programmes, and regulatory strategies that ensure the stability and security of long-term innovative development.

Given this context, the relevance of this research lies in the need to provide a robust, quantitative framework for assessing the impact of innovation-driven supply-side factors on economic growth and innovation-development security. The study seeks to bridge the existing gap in evaluating how classical macroeconomic determinants interact with innovation factors, thereby contributing to the development of a system of indicators for monitoring and managing innovative potential at the national and regional levels.

The structure of the article is as follows. The next section presents a comprehensive literature review, highlighting the research gaps and formulating the study’s objective. The following section on materials and methods outlines the data sources, modelling framework, and analytical tools employed in the study. The results section reports the empirical findings derived from the econometric and system analysis. The discussion section elaborates on the implications, methodological limitations, and cross-country differences. Finally, the conclusion summarises the main findings and proposes directions for future research based on the results obtained.

2. Literature Review

There have been numerous attempts to assess the impact of individual innovation factors on long-term economic development without clearly defining their influence on economic growth. Existing studies primarily examine the relationship between innovative human capital and regional economies [3]; assess living standards and well-being in the context of broader economic growth and technological innovation [4]; investigate technological innovation in the private sector related to the Sustainable Development Goals [5]; and analyse the effects of structural change on innovation by combining Schumpeter’s concept of creative destruction with Kuznets’s lag theory (Environmental Kuznets Curve) [6]. Further studies explore the impact of circular economy components on the economic growth of EU countries [7], and the relationship between innovation and GDP per capita growth in 19 European countries from 1989 to 2014 [8], demonstrating the association between innovation and overall economic development rather than directly with economic growth, which is measured through percentage increases relative to the previous period.

Dahmani and Mabrouki [9] analysed economic growth in the MENA region (1996–2020), focusing on human capital, innovation, governance, capital stock, and labour participation. Using the CS-ARDL model and Granger cointegration tests, they identified significant long-term impacts of innovation, capital accumulation, and governance, while human capital exhibited complex lagged effects, particularly in resource-rich countries. The findings underscore the critical importance of institutional quality and innovation as drivers of sustainable development.

The study by Hardi et al. [10] examined the dual nature of innovation’s impact on economic growth in Southeast Asia, focusing on Indonesia, Thailand, Singapore, Malaysia, and Vietnam. Based on 21 indicators from the Global Innovation Index (GII), the study found that while innovation generally contributes positively to growth, most indicators currently act as constraints, highlighting the necessity for policies that remove institutional barriers and foster innovation-friendly environments.

Aminullah [11] explored the interplay between technological innovation and economic growth using feedback economics and system dynamics modelling. The research emphasised the pivotal role of General Purpose Technologies (GPTs) in industrial policy, advocating post-COVID-19 strategies to promote inclusive growth and reindustrialisation while addressing future coordination challenges.

Thompson [12] developed an innovation-based growth model centred on collective social capital, demonstrating how trust and social networks facilitate innovation and economic growth. The study revealed a self-reinforcing cycle in which cooperation stimulates innovation and profit growth, increasing the ratio of output per worker to innovators – consistent with empirical observations.

A distinct strand of research focuses on the influence of the innovation sector in information and communication technologies (ICT) on economic development, grounded in the Cobb–Douglas production function framework. Jorgenson and Stiroh [13] and Jorgenson et al. [14] represent output (in logarithmic form) as the sum of investment (output of investment goods) and consumption (output of consumer goods) in a given year, determined by the accumulated capital stock (including computer equipment, telecommunications infrastructure, and software), labour, and the effects of scientific and technical progress (STP) on production. However, the precise interpretation of the labour variable remains ambiguous – whether it refers to the number of employed persons or to labour input measured by total compensation and working time – creating dimensional inconsistencies between the left and right sides of the equation, which undermines the model's validity. Furthermore, the model omits the capital utilisation coefficient and fails to account for the time lag between ICT investment and operational deployment. The averaging of macro-factor shares over the study period (1973–1998) introduces distortions that directly affect results. Consequently, information technologies have been shown to exert a positive influence on economic growth and labour productivity but a negative one on total factor productivity (TFP), that is, on the overall efficiency of capital and labour.

A similar study by O'Mahony and Vecchi [15] modifies the previous model for the period 1976–2000 across 31 U.S. and 24 U.K. industrial sectors, assessing the impact of ICT not only on economic growth and labour productivity but also on total factor productivity. Here, output is defined as gross output rather than value added, which significantly alters the relative shares of macro factors and compounds the limitations of econometric estimation. Although capital depreciation is accounted for, utilisation rates are again omitted. Importantly, the authors conclude that methodological inconsistencies significantly affect research outcomes.

Acemoglu et al. [16] employ a standard regression model to assess the relationship between ICT investment and industrial output logarithms in the United States for 1980–2009, incorporating fixed industry effects. However, their findings remain inconclusive regarding whether ICT displaces human labour, arguing that the so-called "Solow paradox" remains unresolved and requires further empirical scrutiny.

Brynjolfsson and Hitt [17] analyse the effects of computerisation on output and labour productivity using data from 527 large U.S. firms between 1987 and 1994. Their modified Cobb–Douglas production function, incorporating both traditional and computer capital, shares similar weaknesses – namely, the substitution of value added for gross output, unclear labour definitions, omission of capital utilisation, and broader econometric limitations.

Finally, Garcia-Herrero and Xu [18] adopt a linear functional form instead of a logarithmic or power function, which substantially departs from empirical reality. Moreover, none of the reviewed econometric models assess the predictive capability of their estimations. To address this gap, the study period should be divided into two subsamples – a training and a testing dataset – allowing for the calculation of model coefficients on the former and validation of forecast error and prediction horizons on the latter.

In addition, it is important to highlight a number of studies that, within the context of the present research, provide a valuable theoretical and empirical foundation for understanding the interrelations between innovation factors, financial mechanisms, and the sustainability of economic growth. Pradhan et al. [19] demonstrated that Europe exhibits endogenous links between innovation activity, venture capital, financial markets, and economic growth. Using a panel vector error correction model (VECM) for 23 European countries over the period 1989–2015, the authors identified mutual dependencies between innovation, venture investment, and financial sector development, all of which contribute to long-term growth. These findings are consistent with our hypothesis that innovation-related macroeconomic supply factors exert a cumulative influence on economic growth and innovation security, particularly within EU member and candidate countries.

Timmis et al. [20] focus on Southern European economies, emphasising the role of innovation ecosystems as instruments for economic recovery and the creation of new value chains. Their "Pipelines for New Chemicals" approach demonstrates how targeted innovation strategies can stimulate regional development and employment, complementing the systemic perspective on innovation as a driver of sustainable growth.

Similarly, Gál [21] investigates the role of innovation in Hungary's regional transformation, showing that regional innovation potential has become a crucial determinant of spatial differentiation in economic growth. These studies collectively underscore the necessity of quantitatively assessing innovation factors at the macroeconomic level, which aligns directly with the objectives of the present research.

Recent scholarship has further expanded the understanding of innovation as a multidimensional driver of sustainable economic transformation. For instance, Dementyev et al. [22] highlight the role of information and innovation interdependencies in structuring the global economic space, demonstrating that technological progress not only enhances productivity but also reshapes power relations in the global innovation system. Similarly, Dzwigol et al. [23] establish the critical relationship between renewable energy, knowledge spillovers, and innovation efficiency, showing that environmental regulation can act as a catalyst for innovation-driven growth.

Within the sustainability and security paradigm, Kharazishvili et al. [24] propose a system of indicators for assessing the environmental component of sustainable development through a security lens – methodologically compatible with the innovation security indicators developed in this study. Meanwhile, Kwilinski [25] explores the nonlinear effects of digital technology on CO_2 reduction, revealing feedback loops between innovation intensity and environmental efficiency, whereas Kwilinski [26] links GDP per capita and foreign direct investment (FDI) to technological leadership, providing empirical evidence of innovation's mediating role between capital inflows and productivity growth.

Further, the works of Kwiliński et al. [27; 28] underscore the dual role of innovation in advancing both green finance and the green economy. Their findings support the proposition that innovation expenditures – particularly in R&D and education – act as pivotal supply-side factors that foster sustainable growth and resilience in EU economies. Complementarily, Szczepanska-Woszczyna et al. [29] demonstrate that higher education serves as a long-term accelerator of innovation capacity, while Thirakulwanich et al. [30] show how policy instruments and green indicators shape cross-national diffusion of eco-innovation in Poland and Thailand, reinforcing the notion of differentiated innovation trajectories.

In organisational and management contexts, Trzeciak et al. [31] reveal how project programme management structures support open innovation at strategic levels, facilitating knowledge transfer and resource coordination across industries. Zastempowski & Cyfert [32] complement this view by evidencing how process innovation strategies within EU transport firms enhance competitiveness and productivity – linking micro-level innovation management to macroeconomic outcomes. Furthermore, Szczyrba & Pacsi [33] highlight the role of serendipity within the innovation cycle, introducing behavioural complexity into innovation dynamics that can influence long-term economic evolution.

Together, these studies form a coherent body of evidence demonstrating that innovation-driven growth depends on both structural and behavioural mechanisms – ranging from financial and regulatory frameworks to educational and technological infrastructures. Their findings substantiate the need for an integrated approach that links innovation inputs (such as R&D and education) with macroeconomic outcomes, particularly within the framework of innovation security and sustainable development. This convergence of economic, environmental, and institutional factors reinforces the analytical framework of the present research, which seeks to quantify the impact of innovation-driven supply factors on economic growth and innovation-development security across EU member, candidate, and former member states.

Thus, the reviewed works form an empirical and theoretical foundation for analysing the influence of innovation-driven supply factors on economic growth and innovation security across Europe, reinforcing the importance of an integrated and multi-dimensional approach as adopted in this study.

The main methodological apparatus employed in the reviewed literature is multivariate regression analysis, which inherently carries a structural pathology arising from the assumption that "the past determines the future." Yet, the future rarely replicates the past; rather, it manifests in fundamentally new forms and structures. Thousands of researchers worldwide continue to refine econometric and statistical techniques in search of representative regression relationships capable of capturing the complex dynamics of economic phenomena. However, as Arrow [34] aptly observed, "trend forecasts, however necessary they may be in practice, are basically a confession of ignorance, and, what is worse from a practical viewpoint, are not policy variables."

This limitation is particularly evident in studies employing the aggregate supply function to evaluate the role and contribution of innovation to economic growth—most often grounded in the neoclassical Cobb–Douglas production function. Analyses of quantitative assessments of innovation factors' impact on growth frequently equate innovation effects with the influence of scientific and technical progress (STP) in various adaptations of the Cobb–Douglas model [35-43]. These studies typically assume a constant rate of STP [37], an assumption that hardly reflects reality and potentially undermines the validity of their results. Consequently, the derived outcomes may apply to an unspecified country within an undefined period, resulting in hypothetical conclusions. Moreover, the distinct impact of innovation factors on economic growth is rarely considered separately. Arrow [34] argues that STP, as an evolutionary process, represents the transformation of numerous individual innovations into broader technological advancements; hence, it should be regarded as an endogenous process rather than an exogenous one.

Thus, in most production functions considered, scientific and technical progress (STP) is treated as a variable dependent solely on time, described metaphorically as "…an ever-increasing exogenous factor of production, falling from the sky like manna from heaven" [41]. According to Kaldor [40], the production function itself is highly contentious and artificial, while STP, in his view, is not subject to quantitative measurement. Therefore, its inclusion in the function as an explanatory variable alongside measurable inputs such as capital and labour is theoretically unjustified. Furthermore, variations in the rate of STP depend on fluctuations in capital dynamics, introducing interdependence and lag effects among explanatory variables, which in turn complicate the accurate characterisation of output growth.

Attempts to quantify the influence of innovation factors on economic growth through the Cobb–Douglas production function have faced substantial criticism [44], casting doubt on the reliability of their conclusions. The main conceptual and methodological shortcomings include:

1. The left-hand side of the equation should represent total output rather than GDP, which reflects only a portion of total production.
2. The use of total employment or total working hours instead of labour input LLL – defined as the product of the effective number of taxpayers and the average annual real wage (W/P) – creates dimensional inconsistencies between the equation's sides.
3. Output generation involves both hired and other categories of workers, whose numbers must be standardised to the equivalent of hired employees based on average wages and total tax contributions, defining the effective number of taxpayers.
4. Capital is subject to depreciation and must therefore be adjusted using the deflator of the previous period, accounting for its consumption and renewal through investment.
5. Since capital utilisation in practice is never complete, a coefficient reflecting the utilisation rate must be introduced.
6. The notion of "average productivity of macro factors" or a "constant average level of technology" remains conceptually vague and practically unmeasurable. This approach produces inherently averaged outcomes and systematic errors, while the corresponding parameter merely serves as a balancing compensator.
7. The application of statistical methods to determine elasticity coefficients introduces averaging errors, diminishing both the scientific and practical validity of the model.

Consequently, in the aforementioned and similar studies, the production function can only be conditionally regarded as a "function," as it does not express a strict causal relationship between variables but rather an empirically derived correlation within a preselected class of functional forms. Such modelling approaches fail to establish direct causality between input and output parameters, offering instead an averaged dependency that may distort real economic dynamics.

Innovation-related factors represent the most promising and sustainable sources of economic transformation, as they underpin advanced technological progress and the transition to higher technological paradigms. It can be reasonably argued that no nation can maintain competitiveness without systematic scientific and innovation support, which is achieved through consistent funding of research and development (R&D), innovation expenditure, and investment in education. Accordingly, the evaluation of innovation factors' contributions, the identification of innovation security indicators, and the formulation of measures to enhance their effectiveness are of strategic importance for policies aimed at ensuring stable economic growth and innovation-driven development.

Although numerous studies have addressed the interplay between innovation and economic performance, significant research gaps remain – particularly concerning the quantification of innovation-driven macro factors within the aggregate supply framework and their direct contribution to innovation security.

Therefore, the purpose of this study is to provide a scientific justification for the quantitative assessment of the contribution of classical aggregate supply macro factors and innovation-related macro factors to economic growth, and to develop resulting indicators of innovation security for potential (Ukraine, Georgia), actual (Poland), and former (United Kingdom) EU member states.

3. Data and Methods

Considering the critiques identified in the literature, the present study employs an aggregate supply model based on a modified neoclassical Cobb–Douglas production function, developed within the Keynesian theoretical framework (where price levels influence economic activity), following the formulation of Tinbergen and Bos [43]. The model incorporates Hicks-neutral technical progress, diminishing marginal productivity of macro factors with limited substitutability, and constant returns to scale [44; 45]. This specification allows for the establishment of a causal–functional rather than purely statistical relationship between input and output variables, thereby eliminating the requirement for long dynamic data series. The model features dynamic elasticity coefficients for labour, capital, and innovation expenditure, as well as a capital utilisation coefficient for each period. It consists of twenty analytical equations [46]. Such a structure enables not the computation of a scalar aggregate supply value, but rather a function of changes in the general price level (GDP deflator), facilitating the estimation of dynamic rates of technical progress and, consequently, total factor productivity (TFP) in each period.

To account for the impact of innovation factors on economic growth, the model was extended following the modification proposed by Kharazishvili et al. [44] to broaden the classical Cobb–Douglas production function. This involves (1) adding innovation-related expenditures to the macro factors of STP, labour costs, and capital expenditures. Specifically, the model incorporates expenditures on scientific and technical activities $G_{NDR,t}$, expenditures on innovation $G_{in.vit,t}$, and expenditures on education $G_{osv,t}$ ($G_{in,t} = G_{NDR,t} + G_{in.vit,t} + G_{osv,t}$).

$$V_t^S(P_t) = e^{\gamma t} L_t^{a_t} K_{zt}^{1-a_t-\beta_t} \left(\frac{G_{in,t}}{P_t} \right)^{\beta_t} = e^{\gamma t} \left[\xi_t N_t(P_t) \frac{W_t}{P_t} k_{sn} \right]^{a_t} (\vartheta_t K_t)^{1-a_t-\beta_t} \left(\frac{G_{in,t}}{P_t} \right)^{\beta_t}, \quad (1)$$

where V_t^S is real aggregate supply output; $e^{\gamma t}$ is scientific and technological progress (STP); γ is rate of STP; L is labour costs; $\xi_t = N_{ef,t} / N_{zag,t}$ is share of the effective number of taxpayers in total employment; $N_{ef,t}$ is effective number of taxpayers (hired employees plus another category of employed individuals, adjusted to the equivalent of hired employees in terms of all taxes and wages; $N_{zag,t}$ is total employment; $N_t(P_t)$ is optimal value demand function, defined by the condition of equality between the marginal product of labour's value and the nominal wage rate; W_t is average annual nominal wage of hired employees; $k_{sn,t}$ is social burden coefficient; ϑ_t is capital utilization coefficient; K_t is capital expenditures; Kz_t - utilized capital; α_t is the elasticity coefficient concerning labour costs; $1-\alpha_t-\beta_t$ is the elasticity coefficient concerning capital expenditures; $G_{in,t}$ is nominal innovation costs; P_t is GDP deflator; t is current period.

The transition from output to GDP (2) is achieved through the technological coefficient of production σ_t defined as the ratio of GDP to output.

$$GDP_t(P_t) = \sigma_t V_t^S(P_t), \tag{2}$$

where $GDP_t(P_t)$ denotes the gross domestic product in period *t*, expressed as a function of the general price level P_t; σ_t is the technological coefficient of production (or the transition coefficient from output to GDP), representing the share of GDP in total output and reflecting the cost structure and degree of intermediate consumption – the higher the σ_t, the greater the share of value added in total output; $V_t^S(P_t)$ denotes aggregate output (aggregate supply) in period t, also expressed as a function of the price level P_t, representing the total volume of goods and services produced before accounting for intermediate consumption.

STP, one of the key factors driving qualitative changes in the economic system, is recognized worldwide as the most important driver of economic development. It is reflected as the result of TFP through the pace of STP γ (3):

$$TFP_t = e^{\gamma_t}, \tag{3}$$

where t denotes the current time period, which represents a flow category, i.e. $t_i - t_{i-1} = 1$ or $dt = 1$.

The rate of scientific and technological progress (STP) corresponds to the difference between the growth rate of output (or GDP) and the rate of growth accounted for by increases in capital, labour, and innovation-related factors, as well as by production technology, which reflects the share of GDP in total output. It serves as an indicator of the unexplained component of economic growth.

To quantify the formalised contribution of innovation factors to economic growth, the Solow residual method is applied. By performing logarithmic transformations and derivatives of the production function (1), while taking into account equation (3), this method provides formalised estimates of each macro factor's contribution to overall economic growth [44]. Based on these estimates, appropriate regulatory and policy measures can be developed. (In the subsequent formulas, the time index t is omitted for simplicity but is implicitly assumed):

Therefore, the contribution of STP to the growth rate of output embodied in labour is (4):

$$Tempo\_L = \dot{a}(\ln\xi + \ln 0.001N + \ln 12W - \ln P + \ln ksn) + a\left(\frac{\dot{\xi}}{\xi} + \frac{\dot{N}}{N} + \frac{\dot{W}}{W} - \frac{\dot{P}}{P}\right), \quad (4)$$

The contribution of STP embodied in capital is (5):

$$Tempo\_K = \dot{a}\beta(\ln\vartheta + \ln K) + \dot{\beta}a(\ln\vartheta + \ln K) + (1 - a - \beta)\left(\frac{\dot{\vartheta}}{\vartheta} + \frac{\dot{K}}{K}\right), \quad (5)$$

The contribution of STP embodied in innovations is (6):

$$Tempo\_Innov = \dot{\beta}(\ln G_{inn} - \ln P) + \beta\left(\frac{\dot{G}_{inn}}{G_{inn}} - \frac{\dot{P}}{P}\right), \quad (6)$$

where $\frac{\dot{\xi}}{\xi}$, $\frac{\dot{N}}{N}$, $\frac{\dot{W}}{W}$, $\frac{\dot{\vartheta}}{\vartheta}$, $\frac{\dot{K}}{K}$, $\frac{\dot{P}}{P}$, $\frac{\dot{G}_{inn}}{G_{inn}}$, $\frac{\dot{k}_{sn}}{k_{sn}}$ are the rates of corresponding variables; $\dot{a}$, $\dot{\beta}$, are the derivatives of elasticity coefficients concerning labour costs and innovation expenditures; N is expressed in millions of people; W is UAH (Ukrainian Hryvnia) per month; all other monetary values are in billions of UAH; $\ln k_{sn} = const$. The growth rates of the specified variables are calculated using the appropriate deflators for the current period (for output and wages) and the previous period (for capital).

Knowing the contribution of each factor to the economic growth of output or GDP, one can determine the rate of STP for the GDP or output equation as the "Solow residual:"

For the GDP equation (2):

$$Tempo\_STP = Tempo\_GDP - Tempo\_L - Tempo\_K - Tempo\_Innov - Tempo\_\sigma, \quad (7)$$

For the output equation (1):

$$Tempo\_STP = Tempo\_V - Tempo\_L - Tempo\_K - Tempo\_Innov, \quad (8)$$

Thus, STP is an endogenous factor, linked to society's expenditures on labour, the renewal of fixed assets, technical and technological upgrades, organization and improvement of the production process, scientific research, innovation activities, and education. Therefore, it depends on the level of economic development. Furthermore, the contribution of STP to output growth should be associated not only with technological changes but also with organisational, and if interpreted more broadly, with institutional changes.

For the scientific justification of the safe existence boundaries of dynamic systems, the methodology for determining the limit values of security indicators using artificial intelligence methods is applied [47]. According to this methodology, the number of security levels (critical, threshold, and optimal) is linked to the concept of an "extended homeostatic plateau," that is, to the zones of positive, neutral, and negative feedback. The quantitative values of the security levels are determined through an extension of Student's t-test method, adapted for normal, lognormal, and exponential types of distributions (Table 1).

Table 1. Formalised Threshold Vector Values.

Type of Indicator Probability Density Function	Lower Threshold	Lower Optimal Value	Upper Optimal Value	Upper Threshold
Normal	$\mu - t \times \sigma$	$\mu - \sigma$	$\mu + \sigma$	$\mu + t \times \sigma$
Lognormal (tail right)	$\mu - t \times \sigma / k_{as}$	$\mu - \sigma / k_{as}$	$\mu + \sigma$	$\mu + t \times \sigma$
Lognormal (tail left)	$\mu - t \times \sigma$	$\mu - \sigma$	$\mu + \sigma / k_{as}$	$\mu + t \times \sigma / k_{as}$
Exponential (tail right)	$\mu - \sigma / k_{as}$	μ	$\mu + \sigma$	$\mu + t \times \sigma$
Exponential (tail left)	$\mu - t \times \sigma$	$\mu - \sigma$	μ	$\mu + \sigma / k_{as}$

Source: Developed by the Authors Based on Kharazishvili & Kwilinski [47].

To automate the process of identifying the type of distribution based on numerical data, a discriminant method from the class of cluster analysis techniques is applied, using the following criteria: Euclidean distance, Manhattan metric, and Rogers–Tanimoto similarity measure [47].

The data for this study were collected from various information sources and consolidated in accordance with the research requirements. The values of the indicators were determined based on official information sources, model calculations, and expert assessments. The following official databases and statistical institutions were used as data sources: the State Statistics Service of Ukraine [48; 49], the Office for National Statistics [50], the National Statistics Office of Georgia [51], Statistics Poland [52], Eurostat [53], the World Bank [54], the International Monetary Fund [55], the Organisation for Economic Co-operation and Development [56], the United Nations Conference on Trade and Development [57], and the United Nations Development Programme [58].

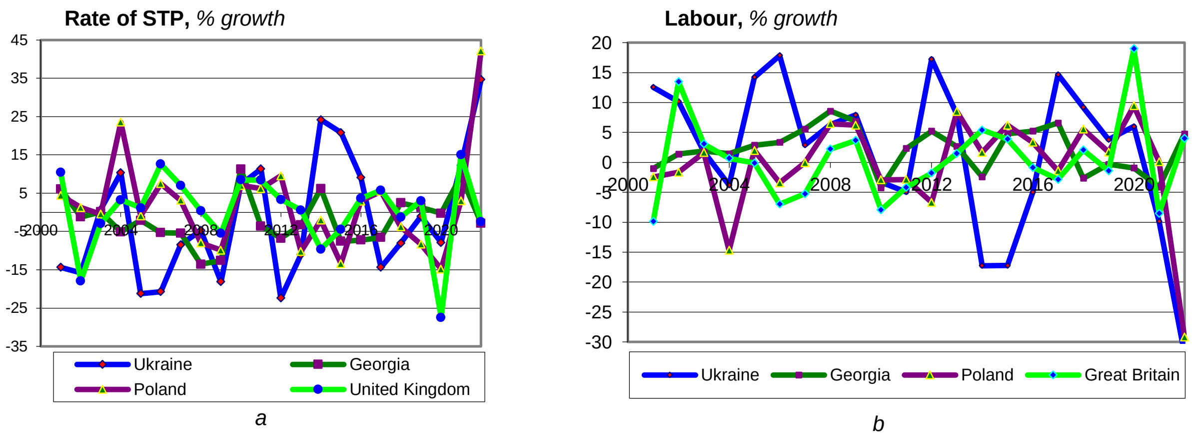
4. Results

4.1. Determining the Contribution of Macro Factors to Economic Growth

The proposed model is universal and applicable to any country, region, or type of economic activity. It requires the following input data to identify the parameters for each current period [46]:

- GDP (for a country), GRP (gross regional product – for a region), or GVA (gross value added – for types of economic activity), at current prices (billion);
- Economic growth rate, % compared with the previous period;
- GDP deflator, GRP deflator, or GVA deflator, % compared with the previous period;
- Technological coefficient of production (the ratio of GDP, GRP, or GVA to total output);
- Capital investment, at current prices (billion);
- Fixed assets (taking into account depreciation, renewal, and revaluation) for the current period, at current prices (billion);
- Consumption of fixed capital, at current prices (billion);
- Population size (million people);
- Average nominal monthly wage, at current prices (UAH);
- Total employment (million people);
- Number of salaried (staff) employees (million people);
- Output of the household sector for other categories of employed persons, at current prices (billion);
- Value-added tax (VAT), %;
- Corporate income tax, %;
- Social security contribution coefficient for wages (SSC).

An example of applying the proposed approach is the quantitative determination of the dynamics of the formalised contribution of macro factors – namely, the rates of scientific and technological progress (STP), production technology efficiency, labour costs, capital expenditures, and innovation-related expenditures – to economic growth in potential (Ukraine, Georgia), actual (Poland), and former (United Kingdom) EU member states. Understanding the contribution of individual macro factors to economic growth provides a basis for developing appropriate macroeconomic policy measures (Fig. 1).



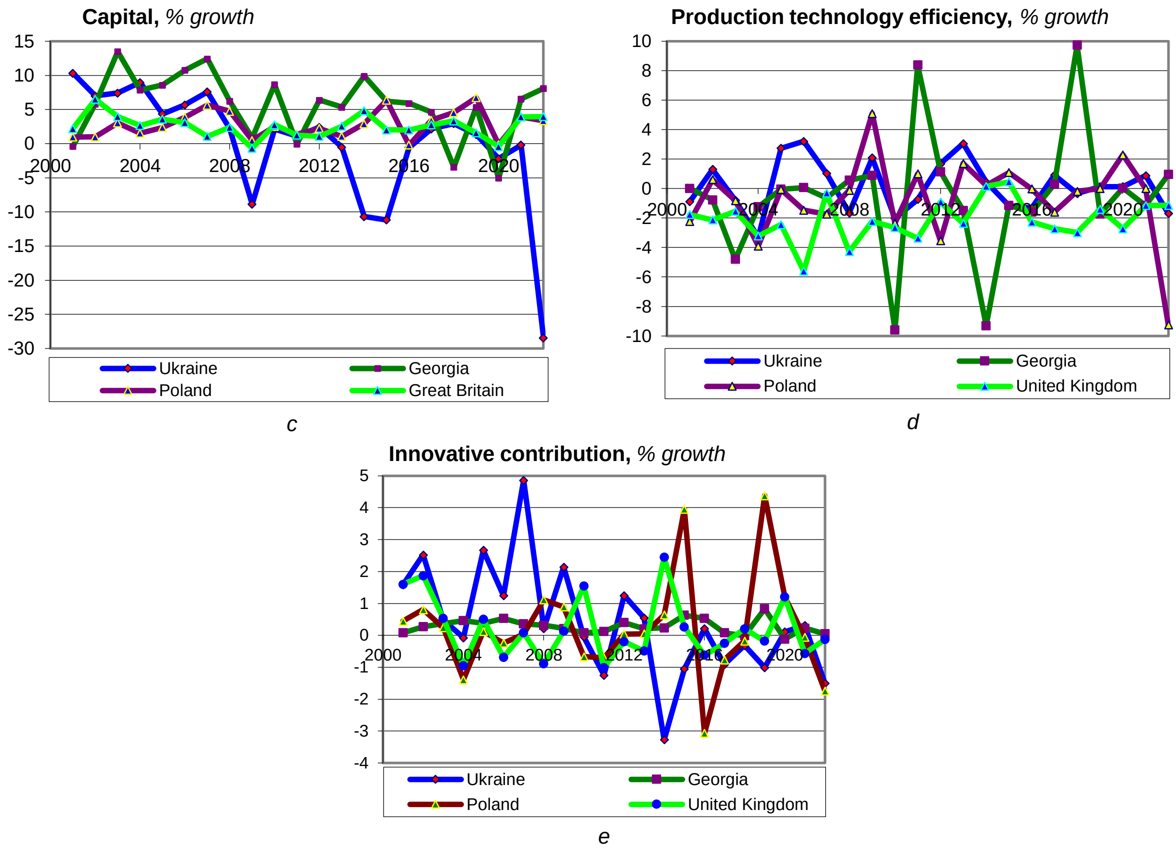


Figure 1. Growth Rates of Macro Factors of Aggregate Supply Contributing to Economic Growth.
Source: Developed by the Authors.

As the calculations indicate, the rates of change of macro factors are not constant but fluctuate across periods. Moreover, each country exhibits its own distribution of the contribution of macro factors to economic growth (Table 2).

Table 2. Cumulative Impact of Aggregate Supply Macro Factors on Economic Growth (% Growth).

Country	*GRP*	γ *pace of STP*	*L* *labour costs*	*K* *capital expenditures*	σ *technological coefficient*	$G_{in,t}$ *innovation expenditures*
			Period 2001-2022			
Ukraine	**17.267**	**-37.385**	39. 390	2.906	3.673	**8.685**
Georgia	**122.200**	**-46.725**	47.826	124.129	-9.284	**6.254**
Poland	**83.200**	**44.071**	-12.501	61.767	-15.24	**5.111**
United Kingdom	**35.000**	**11.355**	9.326	56.497	-46.568	**4.389**
			Period 2012-2022			
Ukraine	**-33.9**	**36.235**	-22.2980	-44.923	2.725	**-5.638**
Georgia	**51.9**	**-15.308**	18.8350	49.909	-4.605	**3.068**
Poland	**39.0**	**10.350**	-0.7378	34.217	-9.269	**4.448**
United Kingdom	**18.9**	**-13.855**	20.4790	27.658	-17.062	**1.680**

Source: Authors' Calculations.

4.1.1. Ukraine

Over the entire 22-year period (2001–2022), the country demonstrates low economic growth rates (0.78% per year) alongside negative rates of scientific and technological progress (STP), primarily due to insufficient funding and the ongoing military aggression of the Russian Federation. The largest contribution to economic growth originates from labour costs, with minimal returns from capital expenditures. Notably, Ukraine exhibits the highest contribution from innovation expenditures among the analysed countries, largely attributable to relatively optimal funding in the education sector. Paradoxically, the most constrained production factor in Ukraine—labour—makes the largest contribution to economic growth, which can be explained by the substantial influence of the shadow economy.

The subsequent 11-year period (2012–2022) is marked by the onset of military actions by the Russian Federation in 2014 and the full-scale invasion in 2022, accompanied by continued underfunding of labour and scientific activities. These combined factors led to severe negative consequences: negative economic growth rates and declines in labour, capital, and innovation expenditures, with only a minor contribution from improvements in production technology efficiency. A distinctive feature of this period is a notable increase in the rate of scientific and technological progress, associated with the advancement of military technologies during the early phase of the war with the Russian Federation.

4.1.2. Georgia

The 22 years (2001-2022) are characterised by average growth rates (5.6% per year), negative rates of STP, and production technology efficiency due to limited support for science and the absence of support for innovation activities. However, there is a significant contribution to economic growth from labour, capital, and innovation expenditures, primarily due to spending on education. The 11-year period (2012-2022) shows approximately the same level.

4.1.3. Poland

The 22-year period (2001–2022) is characterised by an average economic growth rate of 3.8% per year, accompanied by positive rates of scientific and technological progress (STP), with capital expenditures and innovation costs contributing positively to economic growth. However, labour costs and production technology efficiency exerted a negative influence. The 11-year period (2012–2022) demonstrates approximately the same pattern.

4.1.4. United Kingdom

The 22-year period (2001–2022) is characterised by moderate economic growth rates (1.6% per year) and moderate rates of scientific and technological progress (STP). Labour costs and innovation expenditures contributed positively among the countries analysed, while capital expenditures made an average contribution, and production technology efficiency had a negative effect. The 11-year period (2012–2022) shows a similar trend, excluding the negative STP rates observed earlier.

A relatively minor contribution of innovation expenditures to economic growth is observed across all analysed countries, with the greatest fluctuations ranging from –3.3% to 4.8% in Ukraine and Poland (Fig. 1e).

4.2. Forming Innovation Security Indicators

In addition to determining the contribution of macro factors—particularly innovation—to economic growth, it is essential to develop a system of innovation security indicators. These indicators are not published by official state statistical agencies but are derived through economic and mathematical modelling. They play a crucial role in assessing the sustainability and efficiency of innovation-driven development.

4.2.1. The First Indicator

Total Factor Productivity (TFP) – reflects the combined efficiency of all production factors as a result of scientific and technological progress (STP) (Fig. 2a).

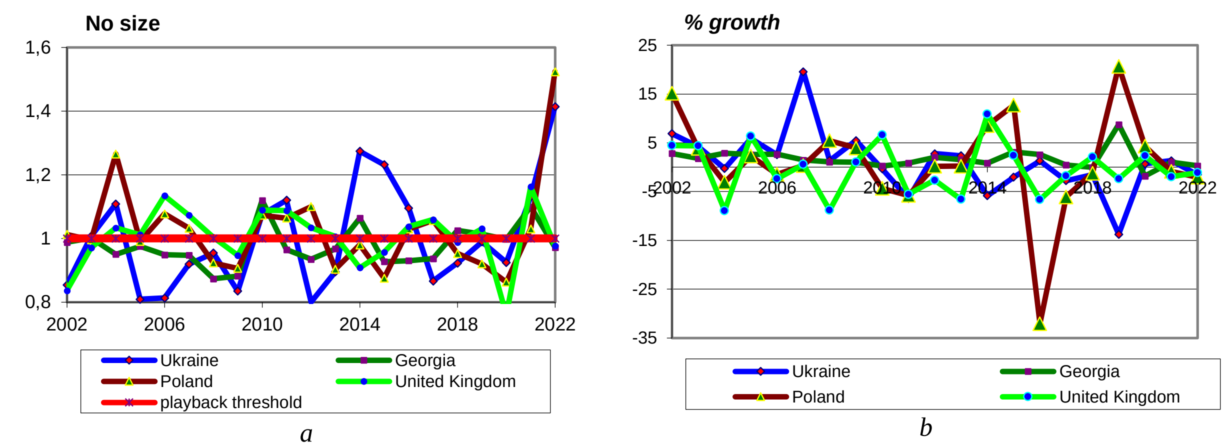


Figure 2. Total Factor Productivity (*a*) and Level of Innovative Contribution to Economic Growth (*b*).
Source: Developed by the Authors.

4.2.2. The Second Indicator

Level of Innovative Contribution to Economic Growth (LIC) – represents the ratio of the growth rate of the innovative contribution to the total contribution of all macro factors.

According to the approach proposed by Kharazishvili et al. (2021), this indicator can be defined as the ratio of the innovative contribution growth rate to the GDP growth rate, or alternatively, to the sum of the GDP growth rate and the innovative contribution growth rate, depending on the signs of both components (9):

$$R_{innov,t}=\begin{cases}\dfrac{Tempo\_Innov_t}{Tempo\_GDP_t}\cdot 100\%, if\ a\ Tempo\_Innov_t>0, Tempo\_GDP_t>0;\\ \dfrac{Tempo\_Innov_t}{Tempo\_GDP_t+|Tempo\_Innov_t|}\cdot 100\%, if\ a\ Tempo\_Innov_t<0, Tempo\_GDP_t>0;\\ \dfrac{Tempo\_Innov_t}{|Tempo\_GDP_t|+|Tempo\_Innov_t|}\cdot 100\%, if\ a\ Tempo\_Innov_t>0, Tempo\_GDP_t<0;\\ \dfrac{Tempo\_Innov_t}{|Tempo\_GDP_t|}\cdot 100\%, if\ a\ Tempo\_Innov_t<0, Tempo\_GDP_t<0;\end{cases}\quad (9)$$

However, we propose to improve this approach, because, at low or zero economic growth rates, which is quite likely, such a ratio yields unclear values – close to 100%, which is difficult to explain. The real GDP growth rate consists of the total sum of the positive and negative growth rates of macro factors of aggregate supply: pace of STP, production technology coefficient, labour costs, capital expenditures, and innovation factor costs.

Therefore, we consider a more adequate calculation of the mentioned indicator as the ratio of the innovative contribution growth rate to the total contribution of macro factors: positive (SP) and negative (SN) (10).

$$R_{inov,t}=\frac{Tempo\_Inov_t}{\sum(SP_t+|SN_t|)}\cdot 100\%, \quad (10)$$

The modelling of the contribution of macro factors of aggregate supply, along with the application of formula (10) for calculating the corresponding innovation security indicator, produces the following results for the analysed countries (Fig. 2b).

4.2.3. The Third Indicator

Efficiency of Innovation Expenditures (EIE) is defined as the ratio of the volume of implemented innovative products ($Q_{in\_p,t}$) to total innovation expenditures ($G_{in,t}$) (11).

$$Ef_{inov,t}=Q_{in\_p,t}/G_{in,t}, \quad (11)$$

Most calculations based on actual statistical data present the following picture of this indicator (Fig. 3).

Following the calculation results, none of the analysed countries demonstrates efficiency in innovation expenditures, except for Poland, which maintained positive efficiency until 2014. The efficiency of innovation expenditures in the United Kingdom ranges from 0.72 to 0.68, in Ukraine from 1 to 0.09, and in Georgia from 0.046 to 0.175, indicating the absence of payback (break-even) for innovation investments.

Considering that it is impossible to protect the vital interests of security entities without identifying the boundaries of safe existence, the threshold vectors of the developed innovation security indicators were determined in accordance with the methodology proposed by Kharazishvili and Kwilinski [47].

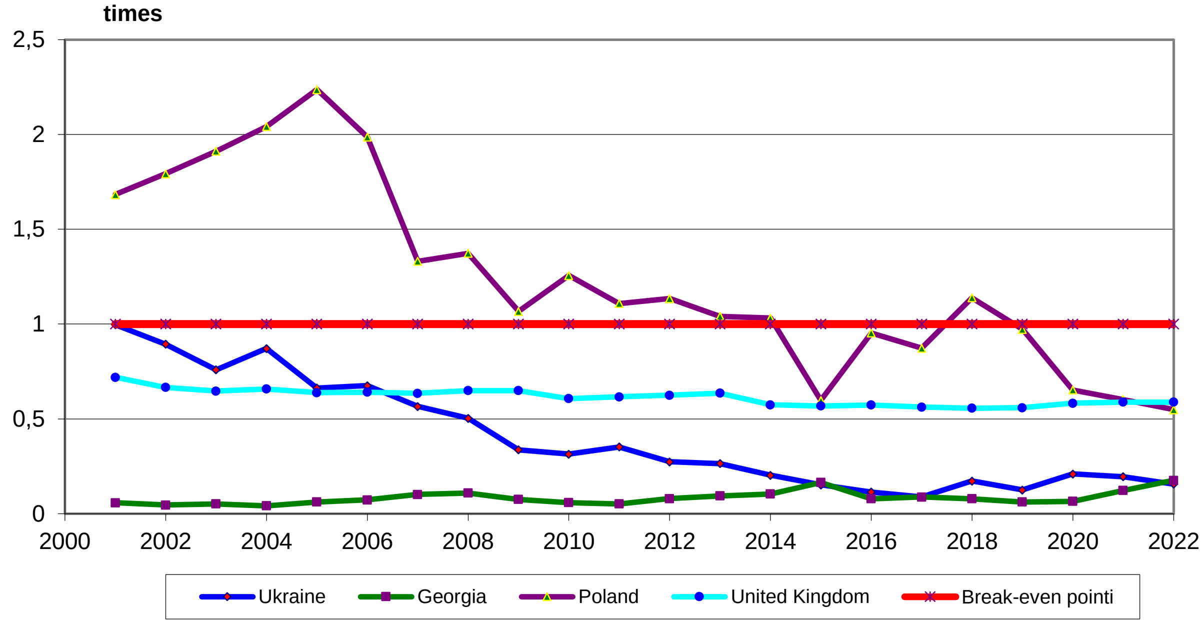


Figure 3. Innovation Expenditure Efficiency.
Source: Developed by the Authors.

As a reference sample for these indicators, values for the countries United Kingdom, Germany, France, Poland, Georgia, and Ukraine were selected and analysed in various combinations (Table 3).

Table 3. Complete Threshold Vectors of Innovation Security Indicators.

Indicators / thresholds	***Critical upper/lower***	***Threshold upper/lower***	***Optimal upper/lower***
- *total factor productivity, no size* (S);	1.558 / 0.903	1.445 / 0.957	1.184 / 1.028
- *the level of innovative contribution to economic growth*, % *growth* (S);	16.700 / -4.810	13.000 / -1.714	5.120 / 0.329
- *efficiency of innovation expenditures, times* (S).	2.518 / 0.600	2.136 / 0.650	1.367 / 1.000

Note: S – Stimulator; D – Dissimulator.
Source: Authors’ Calculations.

According to the calculation results, the following average annual levels of innovation security indicators were obtained for the countries during 2001–2022 and at the end of 2022.

4.2.4. United Kingdom

The average annual TFP value is 1.0096, meaning that, on average, TFP increased the return from macro factors each year. By the end of 2022, TFP was 0.976, placing it in the pre-crisis zone, between the lower threshold and the lower optimal values.

The level of innovative contribution to economic growth was –0.0574% per year; by the end of 2022, it reached –1.1392%, also within the pre-crisis zone (between the lower threshold and lower optimal values).

The efficiency of innovation expenditures was 0.615 times per year; by the end of 2022, it was 0.5889 times, in the critical zone, below the lower critical threshold. Over the entire 22-year period, the efficiency of innovation expenditures remained below the break-even level.

4.2.5. Poland

The average annual TFP value is 1.0279, indicating that TFP consistently increased returns from macro factors. By the end of 2022, TFP was 1.5235, above the upper optimal value (between the upper threshold and the upper critical levels), representing the best result among the analysed countries.

The level of innovative contribution to economic growth was 1.1427% per year; by the end of 2022, it was –2.0355%, in the crisis zone, between the lower threshold and lower critical values.

The efficiency of innovation expenditures was 1.2424 times per year, showing the best return among all countries (optimal zone). By the end of 2022, it was 0.5487 times, in the critical zone, below the lower critical threshold. For 22 years, the efficiency of innovation expenditures was below the reproduction level only seven times (2015–2022, excluding 2018). In all other years, efficiency averaged 1.475 times per year, above the natural reproduction level.

4.2.6. Georgia

The average annual TFP value is 0.9807, meaning that, on average, TFP reduced returns from macro factors, reflecting predominantly negative STP rates. By the end of 2022, TFP was 0.9717, within the pre-crisis zone (between the lower threshold and the lower optimal value).

The level of innovative contribution to economic growth was 1.6919% per year, the highest among the analysed countries; by the end of 2022, it was 0.2979%, almost within the optimal zone.

The efficiency of innovation expenditures was 0.0838 times per year, the lowest level among the countries due to a low level of commercialised innovation products. By the end of 2022, it was 0.1757 times, in the critical zone, below the lower critical threshold.

4.2.7. Ukraine

The average annual TFP value is 0.9956, meaning that, on average, TFP reduced returns from macro factors, indicating predominantly negative STP rates. By the end of 2022, TFP was 1.414, above the upper optimal value (between the upper optimal and upper threshold levels).

The level of innovative contribution to economic growth was 1.0862% per year, indicating that, on average, TFP increased returns from macro factors, suggesting positive STP rates. By the end of 2022, it was –1.5103%, in the crisis zone, between the lower critical and lower threshold levels.

The efficiency of innovation expenditures was 0.4039 times per year, indicating a low level due to weak innovation implementation. By the end of 2022, it was 0.1566 times, in the critical zone, below the lower critical threshold. Over the entire period, efficiency remained below the break-even level.

Hence, based on the calculations, the ranking of innovation security indicators among the analysed countries can be determined (Table 4).

Table 4. Ranking of Countries by Innovation Security Indicators.

Indicators / country	*total factor productivity, no size*	*the level of innovative contribution to economic growth, % growth*	*efficiency of innovation expenditures, times*	*Overall rating*
Ukraine	3	3	3	III
Georgia	4	1	4	IV
Poland	1	2	1	I
United Kingdom	2	4	2	II

Source: Authors' Calculations.

The results of the assessment of country rankings based on the resulting indicators of innovation security show the following order among the analysed countries: Poland, United Kingdom, Ukraine, and Georgia.

5. Discussion

The findings of this study confirm that innovation-driven macroeconomic factors exert a measurable and differentiated influence on economic growth and innovation security across countries at various stages of European integration. The proposed deterministic aggregate supply model, which modifies the Cobb–Douglas production function within the Keynesian framework, demonstrates clear advantages over traditional econometric approaches such as autoregressive or vector autoregressive models [13; 15]. It eliminates the need for long dynamic data series, minimises errors associated with parameter averaging, and provides a causal-functional representation of the relationships between macro factors – capital, labour, and innovation. By combining neoclassical and Keynesian perspectives, the model enhances explanatory capacity and reflects the true interdependencies among macroeconomic variables.

The results are consistent with prior research [7; 8; 19], which confirms the positive relationship between innovation, investment, and long-term economic growth. However, the present study extends these insights by incorporating innovation expenditures as an independent factor of aggregate supply and introducing the concept of innovation-development security. The empirical evidence suggests that Poland demonstrates the highest level of innovation security, supported by strong total factor productivity (TFP) and high efficiency of innovation expenditures. The United Kingdom also exhibits a robust innovation performance, while

Ukraine and Georgia show relatively weaker positions due to underinvestment, institutional fragility, and the destabilising impact of external shocks. These findings are consistent with the conclusions of Kharazishvili and Kwilinski [47], who emphasised the systemic linkage between innovation resilience and national economic security.

For the proposed innovation security indicators, the boundaries of their safe existence were scientifically substantiated – represented as a vector of threshold values – using the methodology for determining the limit values of national security indicators through artificial intelligence techniques [47]. The methodological foundation integrates applied systems theory [59], statistical theory [60], and artificial intelligence methods [61]. Based on the current and threshold values of innovation security indicators, which are not computed by official statistics but may complement the system of innovation development metrics, a comparative ranking was established among the analysed countries, demonstrating the following order of significance: Poland, United Kingdom, Ukraine, and Georgia.

As a further direction of research, it is proposed to develop a comprehensive system of innovation security indicators designed to capture the multidimensional nature of innovation performance and resilience. This framework will be grounded in internationally recognised methodologies for innovation assessment, while expanding their analytical capabilities through the inclusion of newly developed indicators such as total factor productivity, the level of innovation contribution to economic growth, and the efficiency of innovation expenditures. The application of an advanced methodology of integral assessment to this system [62] – employing a multiplicative form of the integral index, a combined normalisation method, and dynamic weighting coefficients based on principal component and sliding matrix techniques – will enable the identification of the level of innovative development within the framework of sustainable development objectives, as well as the detection of risks and weak components from a security perspective.

The subsequent stage of this research involves strategic planning through the implementation of a scientific–strategic foresighting methodology, grounded in the principle that "the future is determined by the trajectory towards it." This approach constructs desired development trajectories towards predefined security goals and addresses the inverse problem by decomposing integral indices using adaptive regulation techniques derived from control theory.

In essence, rather than relying on the traditional predictive paradigm – "the past determines the future" – which merely describes "what may happen," this study advances a systemic identification of sustainable development levels and the formulation of a scientifically grounded strategic roadmap – "how to achieve it." This transition from descriptive to prescriptive analysis ensures the dynamic adaptation of all components and indicators that collectively strengthen innovation capacity and national sustainability objectives.

6. Conclusions

This study provides a comprehensive and methodologically grounded framework for quantifying the contribution of innovation-driven supply factors to economic growth while introducing a system of resulting indicators for assessing innovation security. The deterministic model proposed in this research bridges the long-standing gap between theoretical abstraction and empirical implementation by integrating neoclassical and Keynesian approaches within a single analytical structure. This synthesis makes it possible to account for both the market-driven allocation of resources and state-driven regulatory mechanisms influencing innovation performance. By including innovation-related expenditures – namely, R&D, innovation spending, and education – the model captures the multidimensional nature of innovation as both a production input and a systemic driver of sustainable development and competitiveness.

The three proposed indicators – total factor productivity (TFP), level of innovative contribution to economic growth, and efficiency of innovation expenditures – represent a significant conceptual and methodological advancement in understanding the dynamics of innovation security. The introduction of safe existence thresholds, identified through artificial intelligence–based techniques, establishes an objective foundation for diagnosing vulnerabilities and potential threats within national innovation systems. The comparative results reveal marked cross-country asymmetries: Poland demonstrates the highest level of innovation security, followed by the United Kingdom, Ukraine, and Georgia, reflecting differences in institutional maturity, investment levels, and policy effectiveness. These findings underscore the need for differentiated innovation policies that consider each country's structural and economic context. From a theoretical standpoint, this study advances the traditional production function analysis by transforming it into a deterministic causal model that allows for the explicit identification of relationships among key macroeconomic variables. The integration of innovation security indicators into the aggregate supply framework expands the analytical boundaries of growth theory, introducing a new dimension that links innovation performance with economic and national resilience. This approach also contributes to the conceptual development of innovation economics by defining innovation not merely as a technological or financial process but as a measurable and manageable security parameter.

From a practical perspective, the proposed framework offers a valuable diagnostic and forecasting tool for policymakers, allowing for the systematic evaluation of innovation system efficiency and sustainability. The ability to determine safe threshold values for innovation indicators enables early warning of instability, while the model's flexibility facilitates the adaptation of innovation policies to changing economic conditions. It provides a robust methodological basis for strategic planning, resource prioritisation, and the assessment of long-term innovation resilience—particularly relevant for countries undergoing transformation or integration processes.

Despite its strengths, the study acknowledges several limitations. The deterministic nature of the model may simplify real-world stochastic interactions, potentially omitting random shocks and behavioural deviations. Variability in statistical data quality across countries can also affect accuracy and cross-comparability. Future research should therefore expand the model to include institutional and behavioural parameters, allowing for a more complete reflection of innovation dynamics and their social dimensions.

Building on the current findings, further research should develop along three key trajectories. First, applying the model to sectoral and regional levels will uncover structural disparities in innovation performance and diffusion. Second, incorporating dynamic foresight-based simulations will facilitate the design of adaptive innovation strategies that respond to uncertainty and emerging global challenges. Third, exploring the interaction between innovation governance, financial ecosystems, and societal trust will enhance the model's relevance for developing inclusive and resilient innovation systems.

Collectively, these directions position the proposed framework as a foundation for advancing both academic research and practical policymaking. By aligning innovation-driven growth with national security and sustainable development imperatives, this approach contributes to building innovation ecosystems capable of withstanding global disruptions while fostering long-term economic and social prosperity.

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